A STUDY ON DEVELOPMENT OF A LIVE LOAD MODEL FOR COMPACT VEHICLE-ONLY BRIDGES

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ABSTRACT

This study developed a live load model for passenger cars and a truck load of less than 10kN running on compact vehicle-only bridges. This model was based on mixture condition of vehicle type measuring from two venues which have the greatest traffic volumes using WIM (Weigh-In-Motion) System. The span length to be examined is set at 10-100m; simple spans are applied to the positive moment and shear force, and continuous bridges that vary from 10m to 100m each are applied in the case of a negative moment. The proposed live load was developed to satisfy the maximum load effects in a 75-years service period. The live load has a constant safety factor across widely varying spans using bias factor, and includes both the distribution load and 2-axle concentrated loads.

Keywords: Compact vehicle-only road, maximum load effect, live load model

1. INTRODUCTION

Vehicles passing along roadways have widely varying levels of performance, speed, and weight depending on their features. Passenger cars and other compact vehicles are lightweight and fast, whereas freight vehicles designed for logistics/transportation are heavier and slower.

In today's mixed roadways accommodating differing types of vehicles, compact vehicles account for more than 85% of the entire vehicle mix. The design of such roadways (e.g. the geometrical structure of roadways, internal sections of tunnels, below-bridge space, and live load of bridges), however, is determined primarily based on the specifications and performance of freight vehicles, thus generating relatively greater construction costs and making it difficult to manage the roadways. In this sense, building separate roadways for these two vehicle types will help enhance the performance of roadways, and hence there is need for construction of compact vehicle-only roads (CVR).

Used in the design of structures, design load is closely correlated to safety and economic aspects of a structure. If the standard vehicle load suggested in the design criteria for compact vehicle-only bridges fails to fully reflect the characteristics of vehicles that actually run on those bridges, the safety and economics of the bridges will be considerably undermined. In other words, the structures may be damaged if the live load is smaller than that actually applied, while the economic feasibility of compact vehicle-only roads will be otherwise lost as significant expenditure in construction will be required.

This paper collects actual vehicle load data to obtain a vehicle load model of compact vehicle-only bridges and analyzes their maximum load effects. On this basis, this paper seeks to suggest a live load model for compact vehicle-only roadways/bridges that can be applied to bridges with a span length of less than 100m.

2. METHODS FOR DEVELOPING LIVE LOAD MODEL

Given the unique factors related to vehicles running on compact vehicle-only vehicles, this paper suggests the following basic objectives to build a live load model for building more cost-effective and safer bridges.

First, the live load should have a constant safety rate across widely varying spans. It is difficult to generalize a live load, as the types of vehicle differ greatly and even the same vehicle types have different levels of loading weight, maximum number of passengers, and driving speed. Furthermore, design span lengths differ for individual vehicle types. Hence, this paper aims to develop a factor of safety that is safe enough but not excessively conservative for wide-ranging loads and spans. The maximum span for ordinary roadways/bridges is 200m. However, to maximize economic feasibility, the factor of safety may be examined within a smaller span range of 100m and the same factor of safety can be applied to spans that are greater than 100m.

Second, an economically feasible and safe load that befits the design life cycle of bridges should be developed. If the live load model is smaller than the actual load, the safety of the bridge may be endangered; conversely, the bridge may be planned to have larger sections than needed and therefore will be less economical. Thus, this paper aims to determine loads that ensure the safety and economics of bridges during their target life cycle. The target life of bridges is set at 75 years.

Third, load patterns that are easy to use in the design process and are familiar to designers should be developed. Designers are prone to make errors if varying load patterns are applied, and as such it is desirable to utilize load patterns that are as similar as possible. In determining load patterns, wheel and lane loads may be calculated separately—as specified in the current design standards for roadways/bridges—and the greater value between them can be applied, or distributed and concentrated loads may be placed at the same time, as described in the LRFD design technique. The load proposed in this paper is set as the latter, and is identical to the load pattern of the reliability-based design technique, which is currently under development.

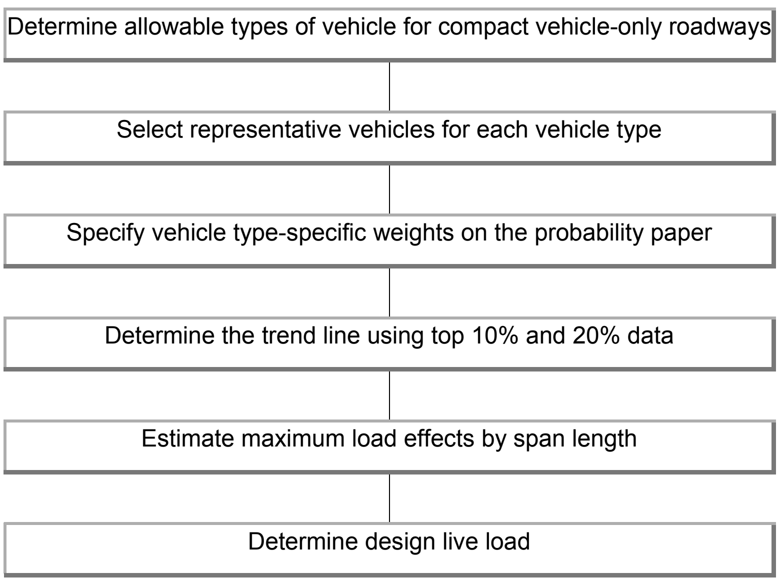


Figure 1. Procedure for development of design live load model

To meet these conditions, it is essential to estimate the maximum predicted weights of vehicles that may be generated during the economically feasible design life of bridges and determine a design live load that consistently fulfills the corresponding load effects (i.e. maximum load effects). The maximum load effects should be calculated for both single vehicles and those running in tandem; this paper develops a design live load model based on the procedure specified in Figure 1.

3. SELECTION OF REPRESENTATION VEHICLES

During their target life cycles, bridges face complicated forms of load from the wide-ranging vehicles running on them. To rationally model these loads, this paper selects the following five major governing factors: (a) vehicle type; (b) vehicle weight; (c) combination of vehicles running in tandem; (d) load distribution of axle load; and (e) distance between vehicles. Among these governing factors, the distance between vehicles and load distribution of axle load can be obtained on the basis of arithmetic means.

First, the types of vehicle that are allowed—or not allowed—to run on the compact vehicle-only roads should be defined. Pursuant to the definition of compact vehicles in the newly revised "Rules on Roadway Facilities and Standards," the allowable vehicle types are specified as passenger cars, compact vehicles, emergency rescue vehicles, and ambulances; they are also defined as shown in Table 1 according to the classification of vehicle type that may run on compact vehicle-only roadways.

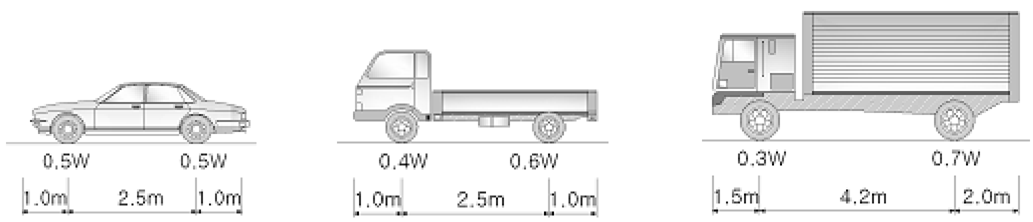
Table 1. Vehicles on compact vehicle-only roads

	Applicable vehicles	Remarks
Allowed vehicle types	Passenger cars, SUVs, small-sized freight vehicles, etc.	Ordinary driving
Special vehicles	Wreckers, ambulances, fire engines, military vehicles, etc.	Emergency rescue
Maintenance vehicles	Snowplow vehicles, aerial lifts, finishers, rollers, etc.	Maintenance /construction

Except for those vehicles allowed to run on compact vehicle-only roads, special, maintenance, and construction vehicles are assumed to be running alone; allowable vehicles are assumed to be passenger cars and Type 2 vehicles with a truck load of less than 10kN.

As for the characteristics of applicable vehicles, their axle weight distributions and inter-axial distances are determined based on specification surveys and relevant research data. In the case of passenger cars and other equivalent vehicles, their weights tend to be uniformly distributed, while the weight distribution of trucks is concentrated upon the rear wheel, as they have greater dead weight.

According to a survey of results obtained with the WIM system, inter-axial distances stand at 2.7m for passenger cars and 2.63m for freight trucks below 10kN. This paper, however, sets the inter-axial distance at 2.5m, as it is more reasonable to simplify the load model within a range that involves less deviation. These values fall within the safety range of 2-3%. With domestic and international design standards as a reference, the inter-axial distance for emergency and maintenance vehicles is set at 4.2m. On this basis, this paper determines the model for representative vehicles as shown in Figure 2.



Passenger car 10kN truck Maintenance and emergency vehicle

Figure 2. Representative vehicle models by type

With respect to the distance between vehicles, this paper refers to existing research results of statistical analyses on Japan's Hanshin Expressway and Korean national roadways. The inter-vehicle distance in Korea is less than half that observed in Japan. Shorter distance between vehicles generates greater load effects for the bridge, and therefore a distance of 1.2m (i.e. during traffic congestion) is applied.[1]

4. SURVEY ON VEHICLE LOAD AND DRIVING PATTERNS

Among the governing factors for loading, vehicle type-specific loads have wide-ranging distributions depending on the self-weight of vehicles and the volumes of dead weight, and thus a probabilistic analysis should be carried out in this regard. The size of load also varies according to a combination of vehicle groups running in tandem. Therefore, the probabilistic analysis should also be made on this governing factor.

To examine the weights of vehicles running on the roadways, this paper measures vehicle weights from a weight-in-motion (WIM) system installed on the Central Inland Highway. The conventional bridge weigh-in-motion (BWIM) system, which has been widely used in previous studies and is based on the displacements of bridges, is considered unsuitable here in obtaining basic data on the loads of compact vehicles. This is because heavy freight vehicles generate noise on displacements while passing through the bridges, making it difficult to accurately discern data for compact vehicles from others, and because fixed load, impact load, and several other factors result in estimation errors. In other words, the bridge superstructures experience structural damping but continue to vibrate after the passage of heavy vehicles, and this corresponds to or is offset by the vibration cycle of compact vehicles passing the bridges. In this case, the size of weights for those compact vehicles may be over- or under-estimated, making it difficult to accurately examine the loads of compact vehicles. For this reason, load data here are obtained from a WIM system based on loop and piezo sensors. This paper analyzes data on a total of 60,494 vehicles running on the Central Inland Highway for three days starting on December 18, 2007.

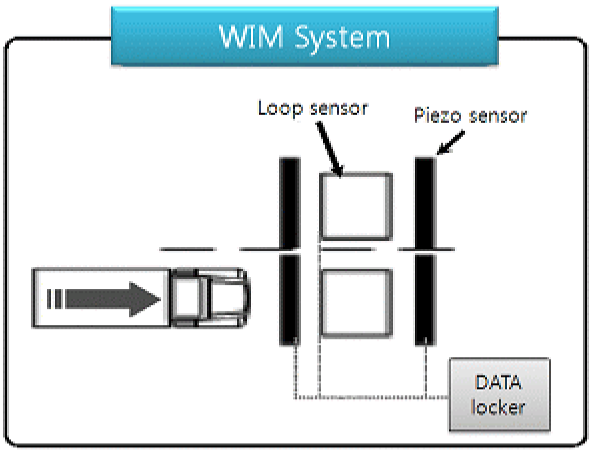


Figure 3. Overview of WIM System

The distributions of vehicle weights on Wednesdays, Thursdays, and Fridays, when the traffic of 10kN trucks is high, are presented in Figures 4 and 5. The frequency of driving for passenger cars is much greater than that of 10kN freight trucks; compact vehicle-only roads have no limits on dead weight, and thus the weights of 10kN trucks, which may be overloaded, have greater influences than passenger cars.

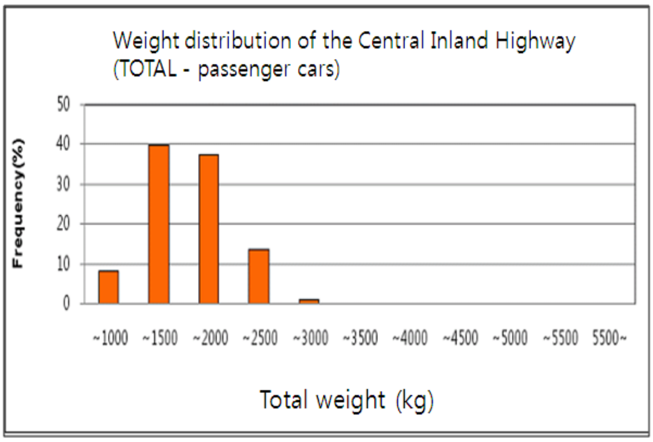


Figure 4. Weight distribution of passenger cars

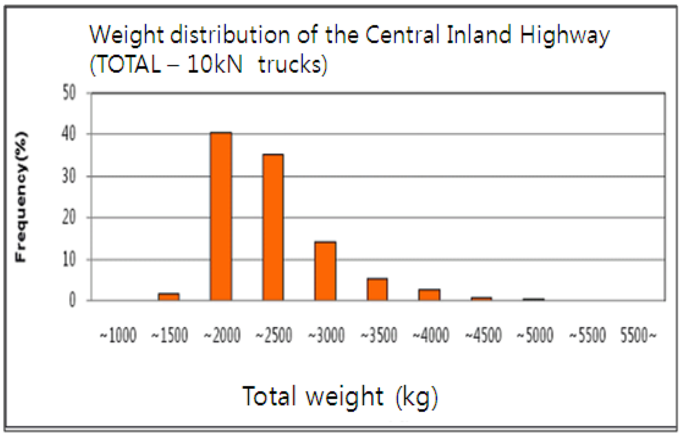


Figure 5. Weight distribution of 10kN trucks

Another factor that influences load is the combination of vehicles running in tandem. Few passenger car drivers tend to drive behind large-sized freight vehicles, and hence the probability of freight vehicles running in the behind position is higher than the mixture rate calculated based on arithmetic means.

The characteristics of vehicles running in tandem are analyzed by choosing two places with large car traffic and video recording the actual traffic volumes there. The venues for measurement are Pangyo IC on the Gyeongbu Highway, which has the greatest traffic volumes, and Namyangju IC on the Outer Ring Circular Highway, where the mixture rate of 10kN freight trucks is the highest. In each place, video is recorded for six hours (07:00-09:00; 12:00-14:00; 18:00-20:00) per day; the probability of in-tandem driving is modeled using a Markov chain.[2]

Table 2. Survey results on in-tandem driving rate

Pangyo IC-Singal JCT section

1. Simple mixture rate of vehicle types for vehicles running ahead:

$$[P_{(1)}] = [p_{\text{passenger car}}(1), p_{1t}(1)] = [0.91, \quad 0.09]$$

2. Transition-probability matrix

	Passenger car	10kN truck	TOTAL
Passenger car	18185	1301	19673
10kN truck	1301	193	1945
TOTAL	19673	1945	21618

$$[P] = \begin{bmatrix} p_{\text{passenger car,passenger car}} & p_{\text{passenger car,1t}} \\ p_{\text{1t,passenger car}} & p_{1t,1t} \end{bmatrix} = \begin{bmatrix} 0.84120 & 0.06018 \\ 0.06018 & 0.00892 \end{bmatrix}$$

Topyeong IC-Namyangju IC section

1. Simple mixture rate of vehicle types for vehicles running ahead:

$$[P_{(1)}] = [p_{\text{passenger car}}(1), p_{1t}(1)] = [0.88, \quad 0.12]$$

2. Transition-probability matrix

	Passenger car	10kN truck	TOTAL
Passenger car	14016	1329	15814
10kN truck	1329	236	2165
TOTAL	15814	2165	17979

$$[P] = \begin{bmatrix} p_{\text{passenger car,passenger car}} & p_{\text{passenger car,1t}} \\ p_{\text{1t,passenger car}} & p_{1t,1t} \end{bmatrix} = \begin{bmatrix} 0.77958 & 0.07932 \\ 0.07392 & 0.01313 \end{bmatrix}$$

5. ESTIMATION OF MAXIMUN LOAD EFFECTS

Maximum load effects are analyzed using two conditions: (a) the single vehicle with the greatest weight; and (b) a group of vehicles running in tandem whose load sizes are altered by the probability of in-tandem driving.

The maximum load that results in damage to a bridge is the largest value among probability distribution values on vehicle weight. This paper utilizes the values of the Gumbel exponent to estimate the future extreme values using short-term measurement data. In order to derive maximum weight during the period of use based on the vehicle type-specific data collected, the top 10% and 20% values from the weight survey data are specified by vehicle type in the Gumbel probability paper.

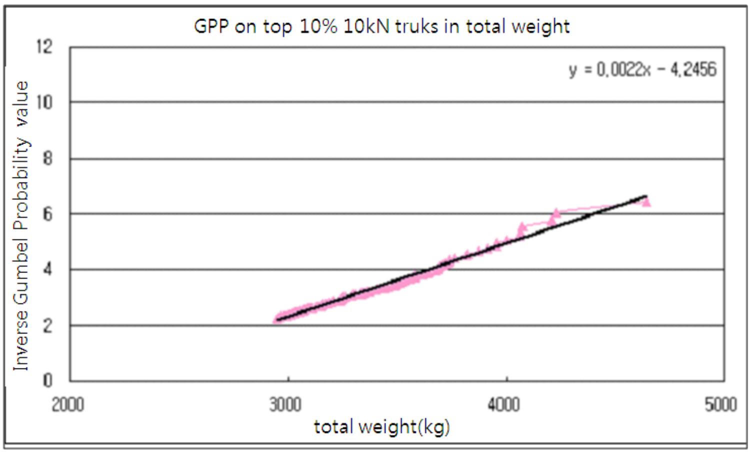


Figure 6. Gumbel probability paper on top 10% 10kN trucks

Equation 1 can be used to convert the probability distribution into a one-dimensional linear formula, and the extreme value of choice can be estimated on this basis. Here, S refers to the probability of occurrence in 75 years.

$$F_S(S) = e^{-e^{-S}} \rightarrow \; S = F_S^{-1} = -\mathrm{Ln}(-\mathrm{Ln}(S)) \qquad \text{(Eq. 1)}$$

Responses that are subject to a maximum load effect analysis are positive moment, shear force, and negative moment. Positive moment and shear force are load effects that have governing influence on most structures; given that a vast majority of bridges are continuous, the negative moment for two-span continuous bridges is included in the maximum load effects that the design live load needs to fulfill. The span length to be examined is set at 10-100m; simple spans are applied to the positive moment and shear force, and two-span continuous bridges that vary from 10m to 100m each are applied in the case of a negative moment.

The types of vehicle that may run in tandem on compact vehicle-only roads are passenger cars and 10kN freight trucks. In order to derive maximum load effects, this study analyzes the load effects for a group of heavy, same-type vehicles and another group of mixed vehicle types running on a long span.

The largest maximum predicted weight is found in the case of single vehicles. For compact vehicle-only roads, vehicle types with the greatest maximum predicted weight as single vehicles are 10kN trucks and maintenance/emergency vehicles. Maintenance and emergency vehicles are assumed to be running alone, as they usually run under controlled situations. The maximum load effects on single vehicles are predominant for maintenance and emergency vehicles compared to 10kN freight trucks.

Meanwhile, the effects of trucks running behind other vehicles may be larger than those of single vehicles if the span is long. Therefore, this paper derives the maximum load effects for individual vehicle types in consideration of in-tandem driving effects.

① Different types of vehicle running in tandem:
- The probability that vehicles of different types and weights run in tandem is determined based on a video recording analysis; the average total weight throughout the period of use that corresponds to this probability level is decided on the Gumbel probability paper.
- The determined vehicles running in tandem are loaded onto simple and continuous beams at an interval of 1.2m (distance between bumpers; 3.2m in inter-axial distance) to calculate the maximum load effects.[2]

② Same types of vehicle running in tandem:
- Vehicles running ahead of and behind each other are assumed to be of the same type and have the same probability of weight.

- The probability that passenger cars and 10kN trucks of the same type run in tandem is analyzed on the basis of video recording.
- Same-type vehicles running in tandem are loaded at the aforementioned vehicle interval to estimate maximum load effects.

The main types of vehicle running on compact vehicle-only roads are passenger cars and 10kN trucks, and therefore the correlations between vehicles running in tandem can be divided into different vehicle types and identical types running under such conditions.[3]

The loads of vehicles running in tandem on a single lane are affected by the possibility of heavy vehicles running behind other vehicles. In other words, vehicles running ahead and behind become correlated. The types of vehicle running ahead may be modeled using the simple vehicle type mixture rate; this state probability distribution is represented in Equation 2, where m is the number for classification of vehicles running on the roadways and $p_{i(1)}$ is the probability of the i^{th} vehicle type being the first to be loaded.[4]

$$[P(1)] = \left[p_{1(1)},\ p_{2(1)}, \dots,\ p_{m(1)}\right] \qquad \text{(Eq. 2)}$$

The types of vehicle running behind are correlated to those running ahead, and thus they can be modeled using the following transition probability matrix:

$$[P] = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} \end{bmatrix} \qquad \text{(Eq. 3)}$$

where $p_{i,j}$ is the probability of the j^{th} vehicle type running behind the i^{th} vehicle type. Based on the total probability theory, the probability distribution of vehicle type that is the second to be loaded on the affected span should be $[P(2)] = \left[P_{(1)}\right][P]$. The probability that n vehicles of the mth vehicle type run in tandem can be calculated using Equation 4, and the results differ significantly from those of a simple mixture rate calculation where the possibility of in-tandem driving is ruled out.

$$P_{m-n} = P_m(1) \times [P_{m-n}]^{m-1} \qquad \text{(Eq. 4)}$$

The probability of passenger cars running ahead is far greater than that for 10kN trucks. In this regard, the possibility of passenger cars running ahead has a governing influence on the maximum load effects, although the maximum predicted weight may differ by individual sections. Using the probabilities of different and identical vehicle types running in tandem, this paper estimates maximum predicted weights for vehicles running ahead of and behind each other—during the period of use and by vehicle type—on the Gumbel probability paper.[5] The probability of passenger cars running in tandem is greater than that of 10kN trucks, and therefore the loads of trucks decline significantly as there is low probability that three or more trucks will run consecutively.

Passenger cars are aimed primarily at carrying passengers, and thus their trends of predicted weight will likely be different from the weight characteristics of freight vehicles. In the case of freight vehicles, they may be loaded with maximally large freight volumes depending on their loading capacity. Passenger cars, on the other hand, are usually designed for 5-15 persons, and the comfort of passengers—as opposed to freights being loaded—is an important factor to be considered. In this sense, they are not likely to carry weights over predetermined levels unless under extraordinary circumstances; unlike freight vehicles, their loads are projected not to increase in a probabilistic manner but to converge to a certain value. According to the actual measurement data on vehicle weights, vehicles with a weight of less than 40kN cover the entire scope of the distribution for vehicle weight. This value, however, refers to the present state, and therefore an increase coefficient of 1.2 is applied to estimate the maximum predicted weight for the future. On this basis, this paper believes 50kN is the ceiling for the maximum weight of passenger cars.

This paper calculates load effects at each span length, with passenger cars running ahead and with passenger cars and vehicles having a maximum predicted weight of 10kN running behind. This paper also integrates the maximum load effects of single vehicles and those running in tandem. On this basis, the maximum load effects for individual spans are determined as shown in Figure 7.

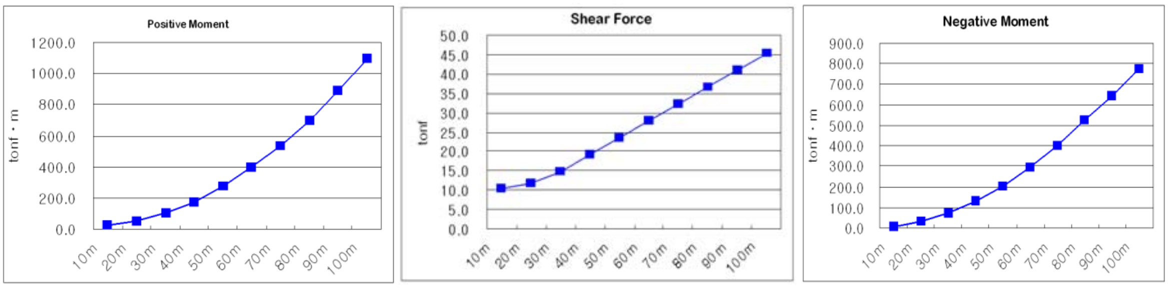


Figure 7. Maximum load effects

6. DETERMINATION OF DESIGN LIVE LOAD MODEL

The proposed design load includes both the distribution load and concentrated load, which are identical to those found using the reliability-based design technique, an approach that is currently under development. This paper also ensures certain levels of safety for each span length by employing load and load/resistance factors.[6] In order to meet these conditions, the design live load should have a uniform bias factor for each span length; the following is used to review the level of load:

$$\text{Bias Factor} = \frac{\text{Maximum load effects}(\text{M}, \text{Vm}, \text{M}_\text{n})}{\text{Load effects driven by (truck load + uniformly distributed load)}}$$

Bias factor is the ratio of design live load against maximum load effects, where the truck load is set at 3.5tonf (i.e. 35kN), which is the weight limit for compact vehicle-only roads, and a uniformly distributed load is one with 1.0 in the ratio against maximum load effects in each span. For instance, if the target moment at the 30m span is 994kN-m, a truck load of 35kN and a uniformly distributed load of 6.66kN/m should be placed simultaneously to satisfy the target moment. The bias factor for each span length is examined using a uniformly distributed load of 6.66kN/m at the 30m span; the uniformly distributed load with the smallest bias factor is set as the design live load along with the truck load. The review results on load bias are illustrated in Figure 8.

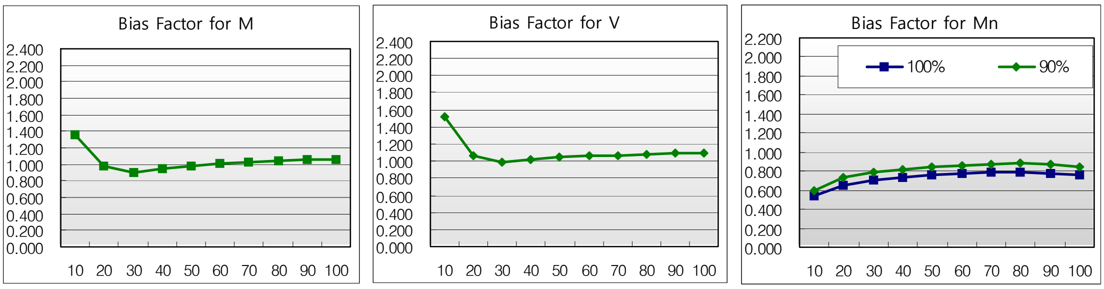


Figure 8. Bias factors of load models

By reviewing bias factors for each span length, it is found that the most consistent bias is observed across different span lengths from a design live load that has a truck load of 35kN, fulfills the target moment of 60m, and overlaps with a uniformly distributed load of 7.6kN/m. The loading patterns and bias factors are as described below:

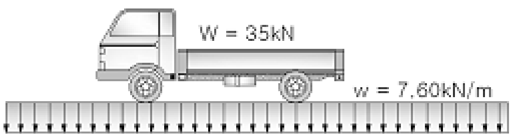


Figure 9. Load model

Using 90% of load effects as the negative moment ratio will be sufficient to achieve conservative level of safety. In the case of AASHTO LRFD, 90% of load effects from concentrated and uniformly distributed loads should be used, and the distance between vehicles is set at 15m.[7] The distance between vehicles at the negative moment section of the proposed load model, however, produces sufficiently safe values even at the position where maximum load effects are found. Hence, it would be fine not to place any limit on the inter-vehicle distance at the negative moment section. When converted into the weights of single vehicles, load effects at a span length of 10m are equivalent to 120kN and those at 30m to 150kN with respect to single driving effects. It would be acceptable to allow emergency and maintenance vehicles below 120kN to drive on compact vehicle-only roads on the condition that they drive unaccompanied by other vehicles.

The design standards for roadways/bridges stipulate that the width of vehicle-occupied areas be 3.0m and the design width of lanes 3.6m at maximum.[8] The width of vehicle-occupied areas under the design standards, I.e., 3.0m, seemingly disperses the vehicle width of 2.5m and the margin of 0.5m onto both sides, with an aim of ensuring driving margins for wider vehicles than the aforementioned vehicle width as well as the minimum interval for ordinary vehicles. Therefore, this paper examines the overall width of unallowable vehicles for compact vehicle-only roadways/bridges and determines the width of areas occupied by vehicles with the margins included. Using 2.5m as the width of vehicle-occupied areas and 3.25m as the width of standard lanes, the design number of lanes for compact vehicle-only roads is set as described in Table 3.

Table 3. Width of design lanes for compact vehicle-only roads

$$\mathrm{W} = \frac{\mathrm{W_c}}{\mathrm{N}} \leq 3.25\mathrm{m}$$

Scope of W_c (m)	N	Scope of W_c (m)	N
$5.0 \leq W_c < 7.5$	2	$20.5 \leq W_c < 23.75$	7
$7.5 \leq W_c < 10.75$	3	$23.75 \leq W_c < 27.0$	8
$10.75 \leq W_c < 14.0$	4	$27.0 \leq W_c < 30.25$	9
$14.0 \leq W_c < 17.25$	5	$30.25 \leq W_c < 33.5$	10
$17.25 \leq W_c < 20.5$	6		

7. CONCLUSIONS

For the design of vehicle-only bridges, the design load (DB-13.5 and DL-13.5) in the design standards for bridges produced excessive economical expenditures. Under this circumstance, this study proposed the relevant vehicle design criteria for vehicle-only bridges.

In order to develop the design live load, the maximum predicted weight during target life of bridge was estimated using Gumble probability paper and the maximum load effects for individual spans were determined using representative vehicles. The effects of vehicles in tandem may be larger than those of single vehicles if the span is long. Therefore, this paper derived the maximum load effects for individual vehicle types in consideration of in-tandem driving effects. As a result, this paper proposes the design live load to satisfy the maximum load effects in a 75-years service period. Based on reliability analysis, the proposed design live loads were then verified to ensure the sufficient factor of safety.

The design live load for vehicle-only bridges proposed in this paper exhibited the constant level of reliability. Thus, the proposed model was applicable for future design standard for vehicle-only bridges. According to the economic analysis of widely-used bridges (such as beam-type bridge, steel composite box bridge), the application of the proposed design criteria was able to reduce construction costs of superstructure by 20 % with comparison to the application of conventional design criteria.

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